Experimental Design

ATR NSUF User Week 2009
Experimenter Course

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Presentation Agenda

- *Experiment Types*
- *Irradiation Requirements*
- *Irradiation Environments*
- *Flux Tailoring*
- *Effluent Monitors*
- *Miscellaneous Issues*
- *Experiment Examples*

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Experiment Types

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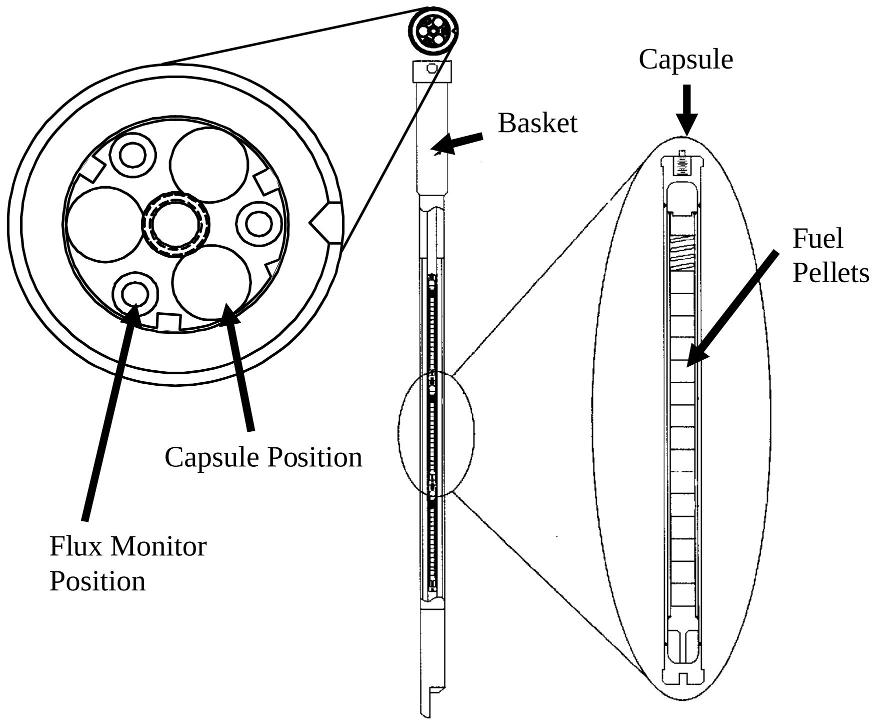
Static Capsules

- *Many are non-instrumented (e.g. radioisotopes)*
- *Can include passive instrumentation (flux wires, melt wires)*
- *Performed in reflector positions or flux traps*
- *Utilized for isotopes, structural materials, or fuel*
- *Lengths up to 1.2 m & diameters up to 12.7 cm*
- *Usually the least expensive testing technique*
- *Six month lead time*



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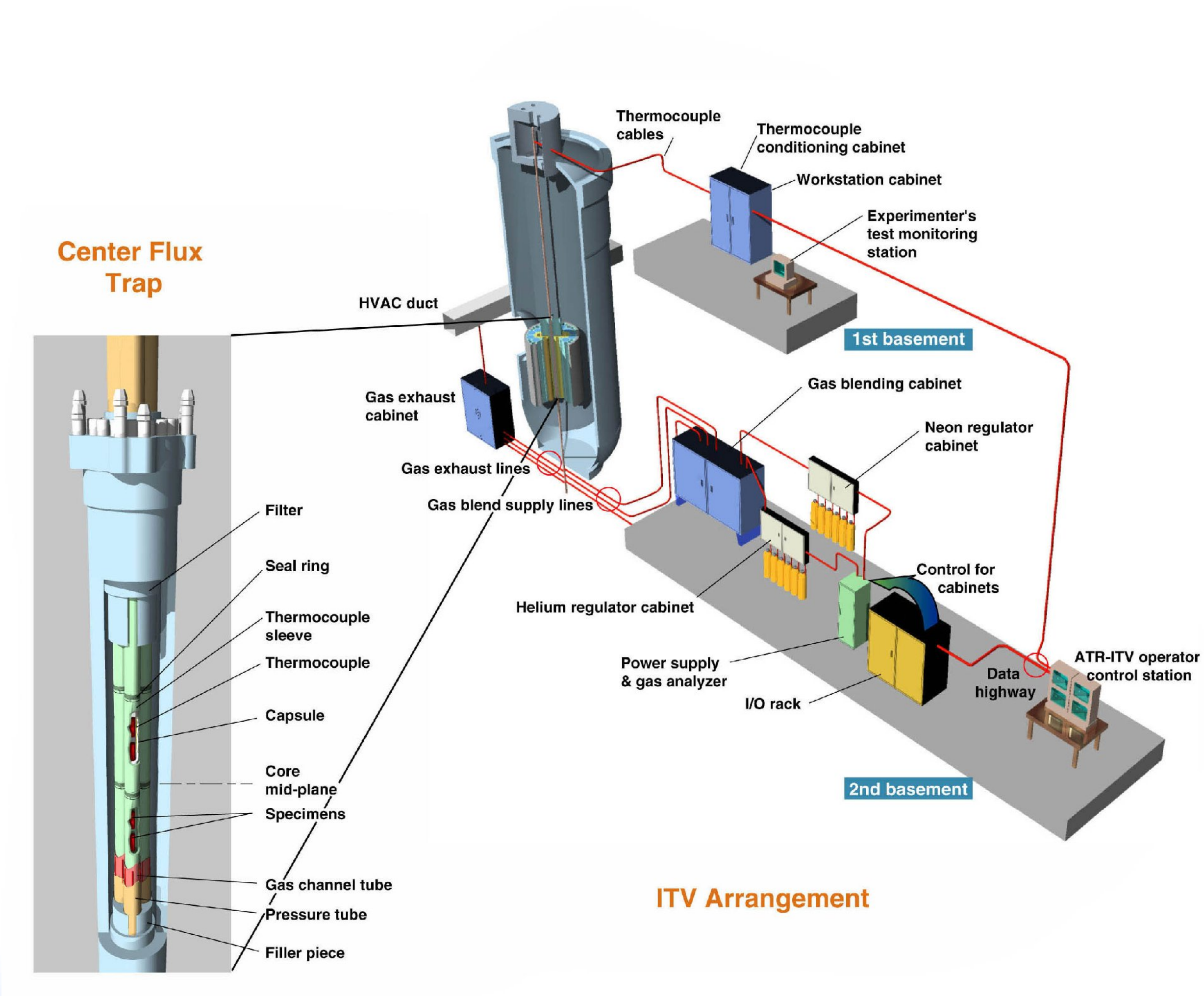
Instrumented Lead Experiments

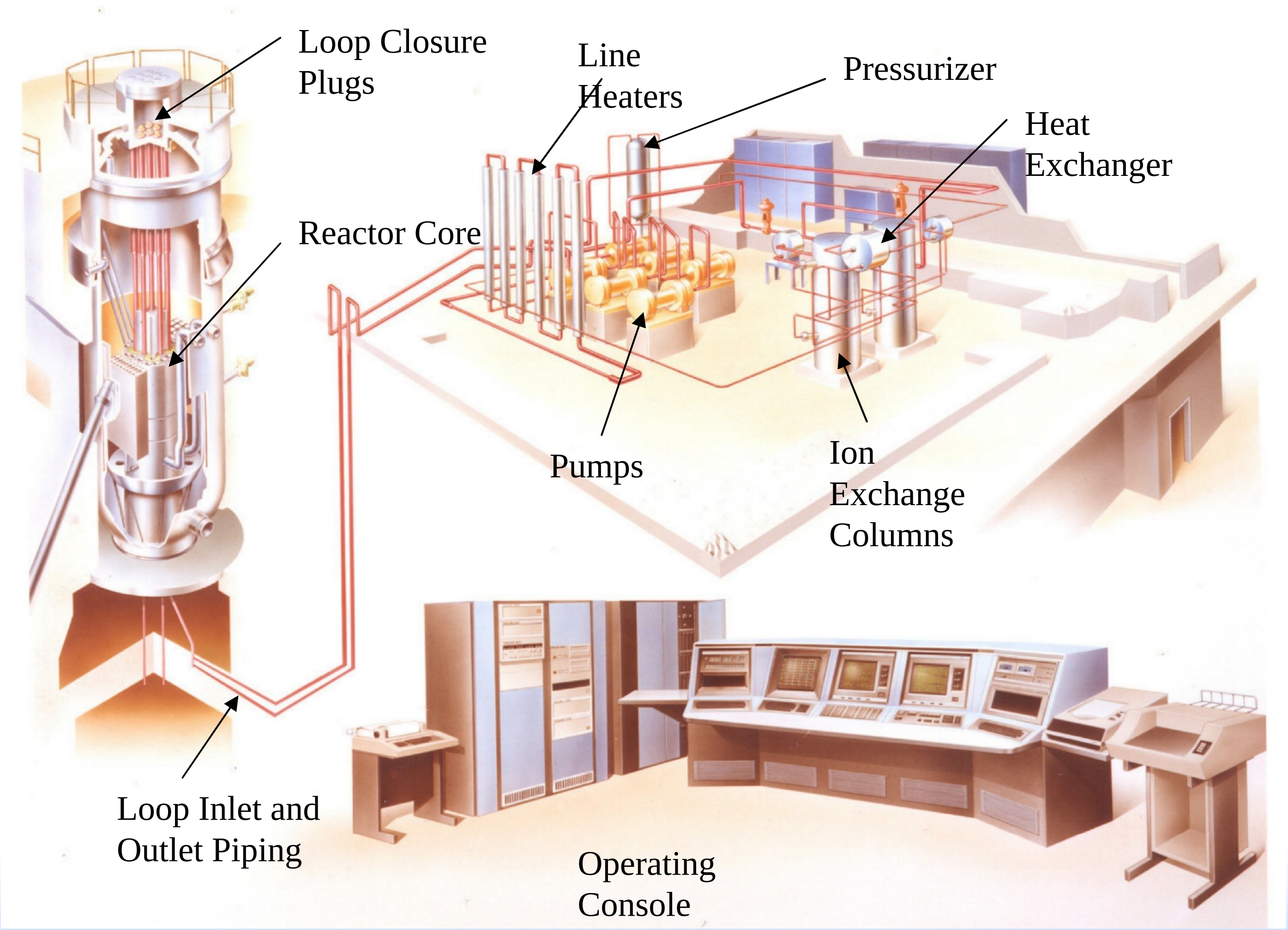
- *On-line instrument measurements (typically temperature)*
- *With or without active temperature control*
  - *Range: 250 - 1000 +/- 5 °C*
- *Utilized in reflector positions or flux traps*
- *Lengths up to 1.2 m & diameters up to 12.7 cm*
- *Structural materials, cladding, fuel*
- *One year lead time*



Pressurized Water Loop Tests

- *Five flux trap positions currently have pressurized water in-pile loop tests (1 large diameter, 4 standard diameter)*
- *Sixth pressurized loop test will soon be installed*
- *Each loop has its own temperature, pressure, flow & chemistry control systems*
- *Structural materials, cladding, fuel*
- *Flux tailoring and transient testing capabilities*
- *Up to two year lead time for new test programs*

Typical Pressurized Water Loop Layout



Experiment Requirements

Irradiation Requirements

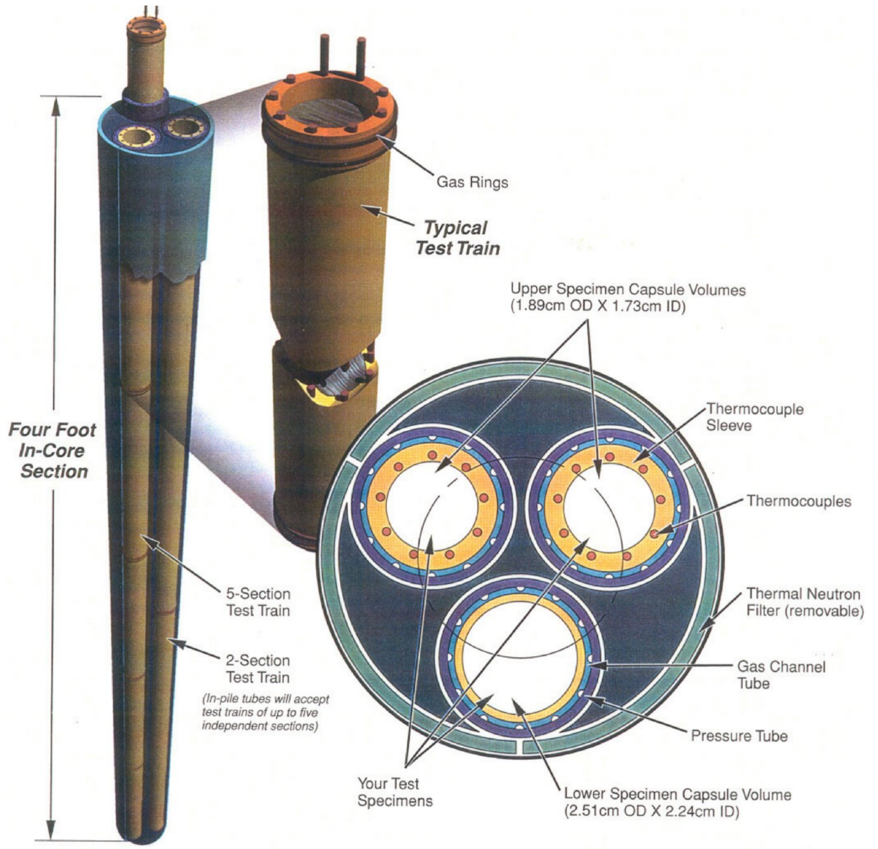
- *Specimen size & shape*
  - *Standard test specimen*
  - *Minimum grains across specimen*
- *Desired fluence*
  - *Fast neutron damage level*
  - *Fuel*
    - *Burn-up level*
    - *Acceleration factor*
  - *Fast/thermal ratio*
- *Desired irradiation temperatures*
  - *Room for gas gap to provide adequate insulation*
  - *Control/monitoring*
    - *Active – gas mixtures & thermocouples*
    - *Passive – calculations with melt wires, silicon carbide, etc.*

Irradiation Environments

- Inert gas - temperature control selections
  - Insulator gas
    - Argon – good temperature range but activation issue
    - Neon – less temperature range but very limited activation - fission gas monitoring
- Non-inert gas
  - Utilize different temperature control gases
  - Utilize second gas boundary and specific cover gas
- Thermal Bonding – liquid metal
  - Reduced temperature gradients in specimens
  - Smaller gas gaps necessary to achieve desired temperatures
- Pressurized water
  - Chemistry control
  - Flow
    - Loop
    - Stagnant – water capsule facility
    - Test reactor PCS

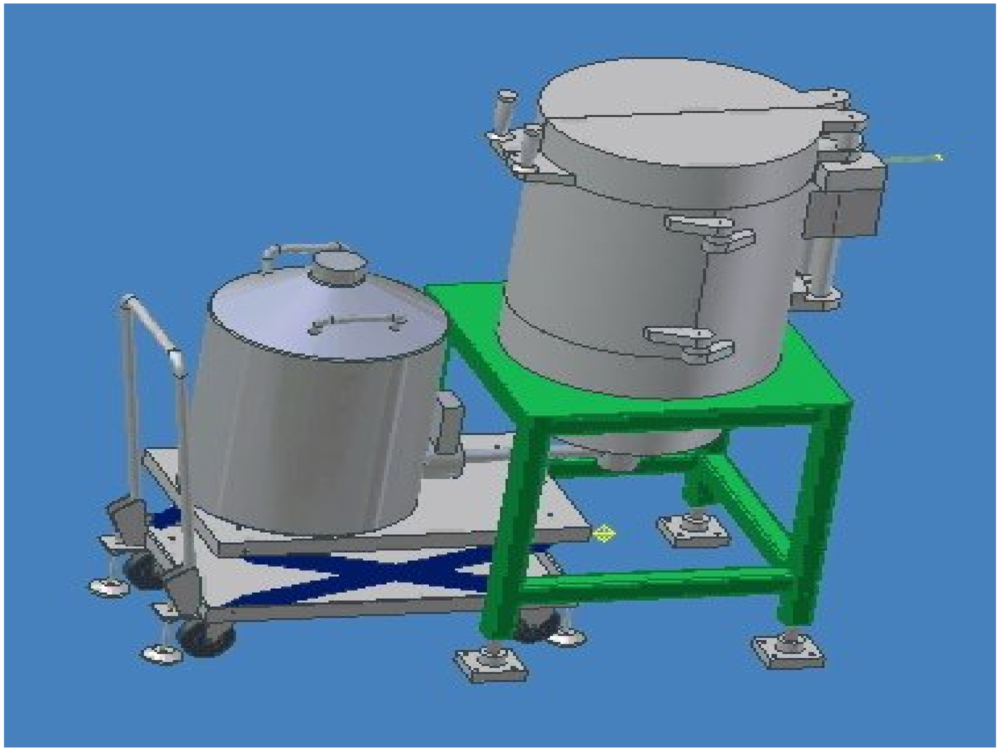
Flux Tailoring

- *Irradiation position*
  - *Close to fuel to increase fast fluence*
  - *Flux trap or reflector to increase thermal*
- *Fixed neutron absorption shroud*
  - *Integral with encapsulation design*
  - *More choices of absorption material if isolated from coolant*
  - *Consumable (e.g. Boron)*
- *Removable/replaceable neutron absorption shroud*
  - *Solid - chemistry compatibility with reactor coolant*
  - *Gas shroud – He3*
- *Booster fuel*



Effluent Monitors

- Fission product monitors
  - Gross gamma detector to identify individual failures (particle fuel)
  - Spectrometer to measure concentration of specific isotopes



- Other monitor options
  - Gas chromatograph for cover gas – Magnox graphite oxidization
  - Monitor radioactive gas (i.e. tritium) for on-line indication of specimen performance

Miscellaneous Issues

- ***Material Selection***
  - ***Compatibility with specimens or irradiation environment (particle fuel, catalyze reactions, etc.)***
  - ***Thermal issues (expansion stresses & clearances, service & design temperatures, brazes)***
  - ***Neutronic or activation effects (flux variations, heating, waste disposal, etc.)***
  - ***Design code requirements***
- ***Marking or features***
  - ***Specimens or specimen holders for identification in hot cell***
  - ***On capsules to provide orientation for installation in core & PIE***
  - ***Cut lines for disassembly of test trains/capsules in hot cell***
- ***Assembly & disassembly***
  - ***Walk through assembly of capsule & test train***
  - ***Consider disassembly in a hot cell - with manipulators***

Experiment Examples

Magnox Generation Graphite Irradiation

Experiment Purpose

Extend data base on Magnox gas reactor graphites to higher density losses and fast fluence damage levels to support life extension of Magnox power stations in UK

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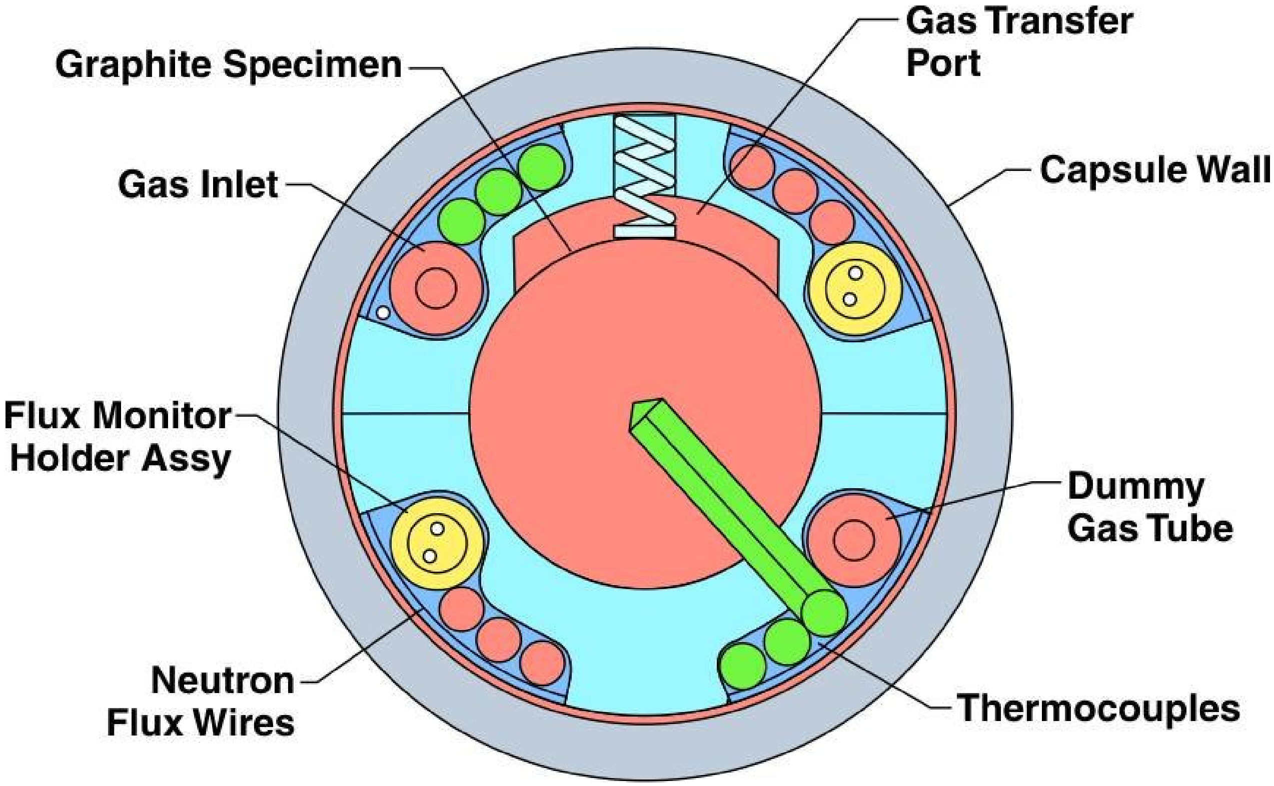
Magnox Graphite Irradiation

- *Standard Magnox graphite PIE specimens (Ø12 mm x 6 mm thick)*
- *On-line temperature indication and control – utilized ITV in CFT*
- *Total nuclear heating dose of 7 x 10^7 joules/gram*
- *Fast neutron dose of 18 x 10^{20} n/cm^2 (E>0.1 MeV)*
- *Two equal size capsules - one oxidizing & one inert, minimize all other differences (e.g. mirror images about ATR core centerline)*
- *Measure fast and thermal neutron flux*
- *Inert Capsule*
  - *99.996% pure helium (< 1 ppm O_2)*
  - *Sample inlet line for O_2*
  - *Sample inlet and exhaust line CO*

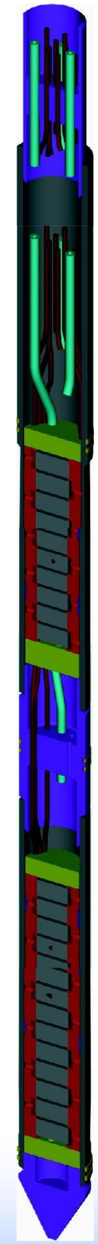
Magnox Graphite Irradiation
(continued)

- *Oxidizing capsule at typical Magnox reactor conditions*
  - *Specimen temperatures of 410ºC at core center to 373 ºC at edge of core*
  - *Maximize graphite surface exposed to gas flow*
  - *Minimize materials that affect graphite oxidation rate*
  - *$CO_2/CO/H_2$ cover gas mixture @ 380 psi*
  - *Provide capability to mix pure CO_2 gas with a mixture of CO and H_2 as needed to control experiment oxidation rate*
  - *Utilize a gas chromatograph to measure and control the $CO_2/CO/H_2$ mixture*
  - *Sample inlet line for O_2*
  - *Sample inlet and exhaust line for CO, H_2, and CH_4.*
  - *Provide capability of purging system with inert (helium) gas*

Magnox Graphite Irradiation
(continued)



Capsule Cross Section



Vertical Section

Advanced Gas Reactor (AGR) Fuel Development and Qualification Program

- *Experiment program purpose is to support development of next generation Very High Temperature Reactors - near term for the Next Generation Nuclear Plant*
  - *Provide irradiation performance data to support fuel process development*
  - *Support development & validation of fuel performance & fission product transport models and codes*
  - *Provide irradiated fuel & materials for post irradiation examination & safety testing*
  - *8 Fuel irradiations currently planned*
- *Purposes of AGR-1 Experiment are:*
  - *Shakedown of test design prior to fuel qualification tests*
  - *Irradiate early fuel from laboratory scale processes*

AGR-1 Fuel & Irradiation Requirements

- TRISO-coated, Uranium Oxycarbide (UCO)
- Low Enriched Uranium (LEU), <20% enrichment
- Particle dimensions
  - 350 µm diameter fuel kernels
  - 780 µm diameter particles
- Burn-up –> Fissions per Initial Metal Atom (FIMA)
  - 18% FIMA (172.8 GWd/t) goal for all compacts
  - 14% FIMA (134.5 GWd/t) minimum
- Fast neutron fluence
  - Minimum > 1.5 x 10^{25} n/m2 (E>0.18 MeV)
  - Maximum < 5 x 10^{25} n/m2 (E>0.18 MeV)

Fuel Particles

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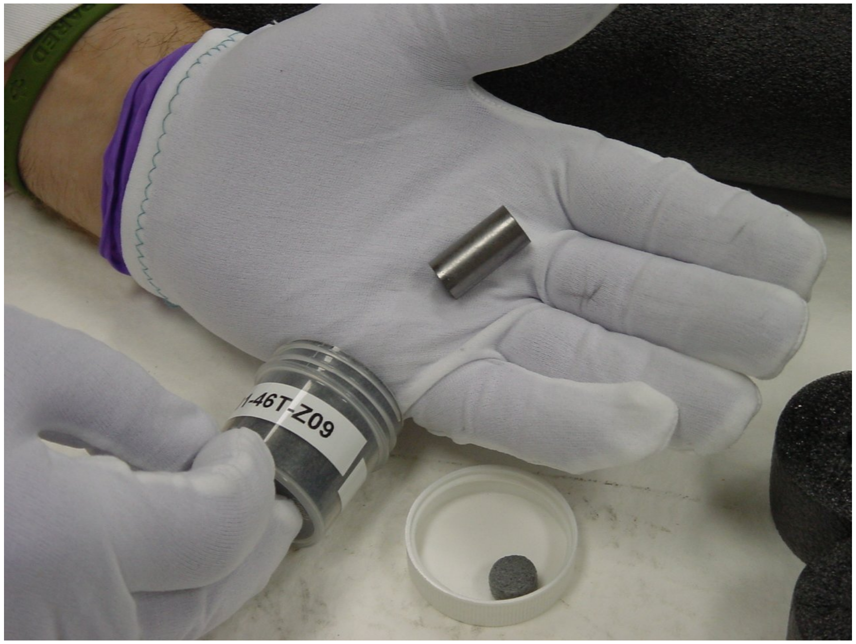
AGR-1 Fuel & Irradiation Requirements
(Continued)

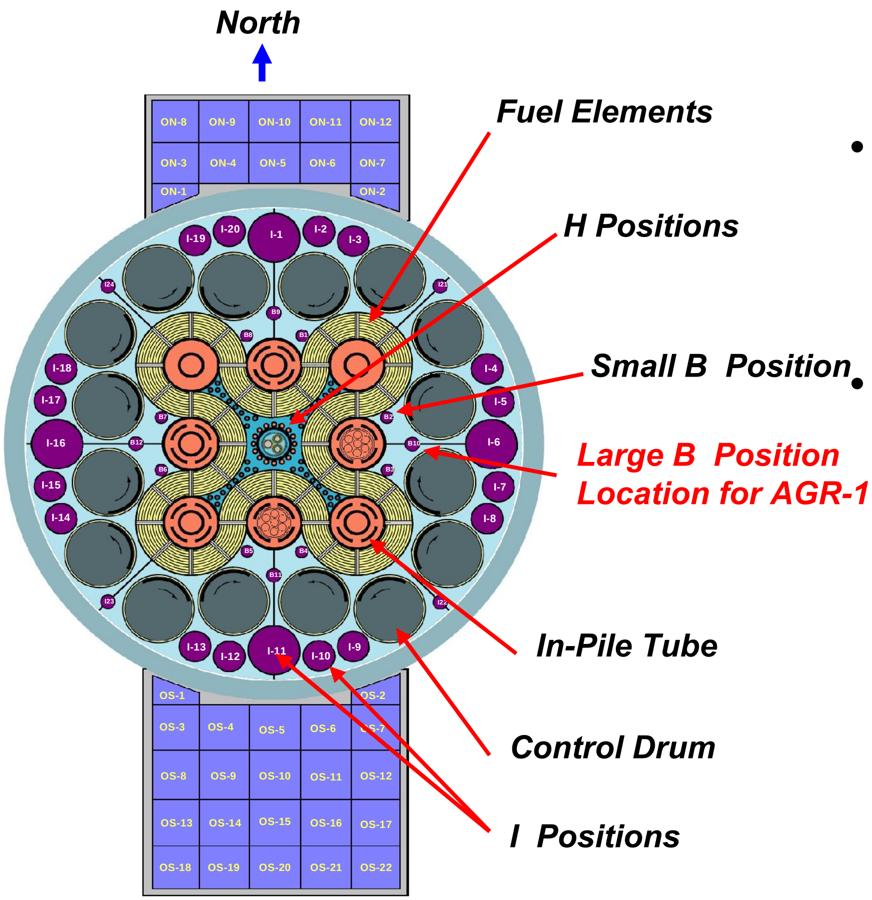
- ***Fuel compact details***
  - ***Right circular cylinder***
  - ***12.4 mm diameter***
  - ***25.4 mm length***
  - ***~4,150 fuel particles/compact***
  - ***~0.9 g U/compact***

- ***Fuel compact irradiation temperature requirements:***
  - ***Time-average, volume-average = 1150 +30/-75 ºC***
  - ***Time-average peak = 1250 ºC***
  - ***Instantaneous peak = 1400 ºC***



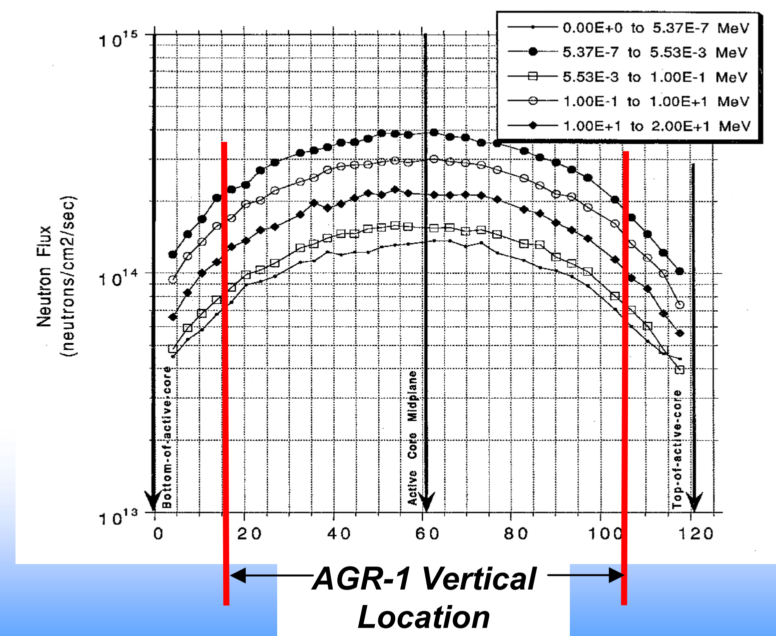
AGR-1 Fuel Compact

AGR-1 Experiment Location in ATR Core



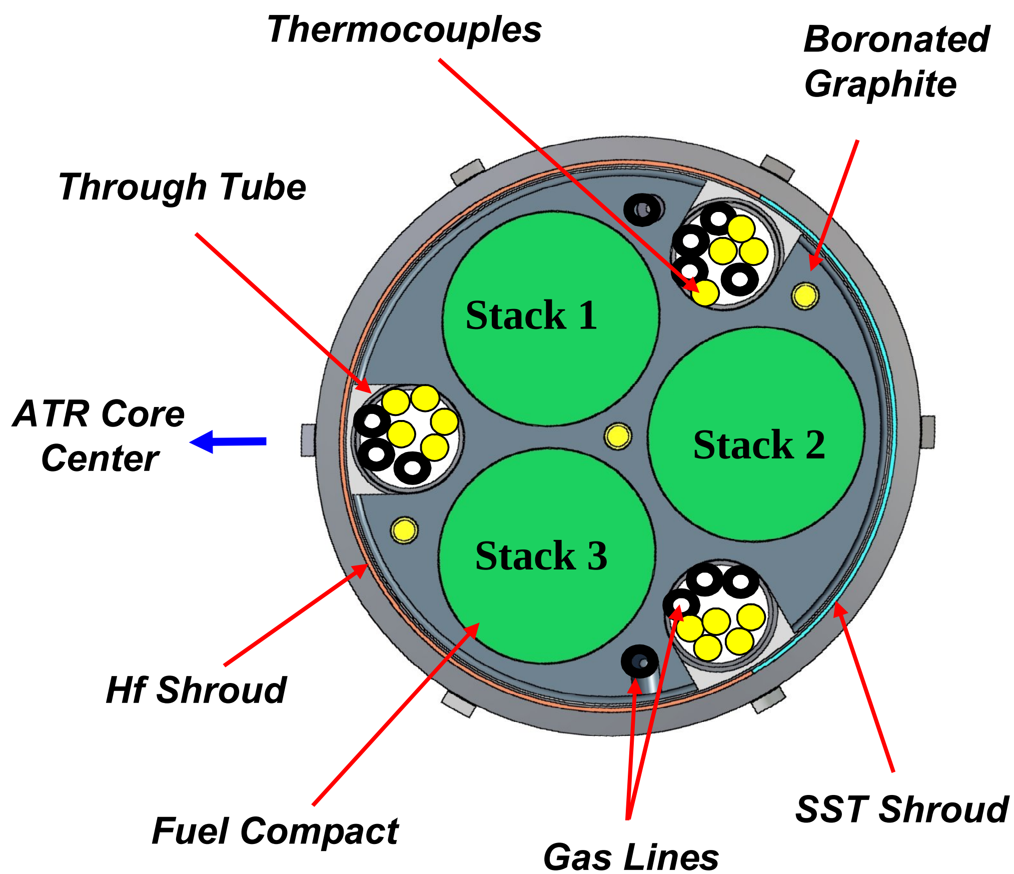
ATR Core Cross Section

- *AGR Program will utilize the large B positions (38mm diameter) in ATR*
  - *AGR-1 in east large B position (B-10)*
- *Large B position flux rate*
  - *Spectrum very similar to NGNP*
  - *Modest acceleration – 2 years in ATR simulate 3 year lifetime for NGNP fuel*
- *Utilize center vertical portion of core where axial flux is most uniform*



AGR-1 Capsule Design Features

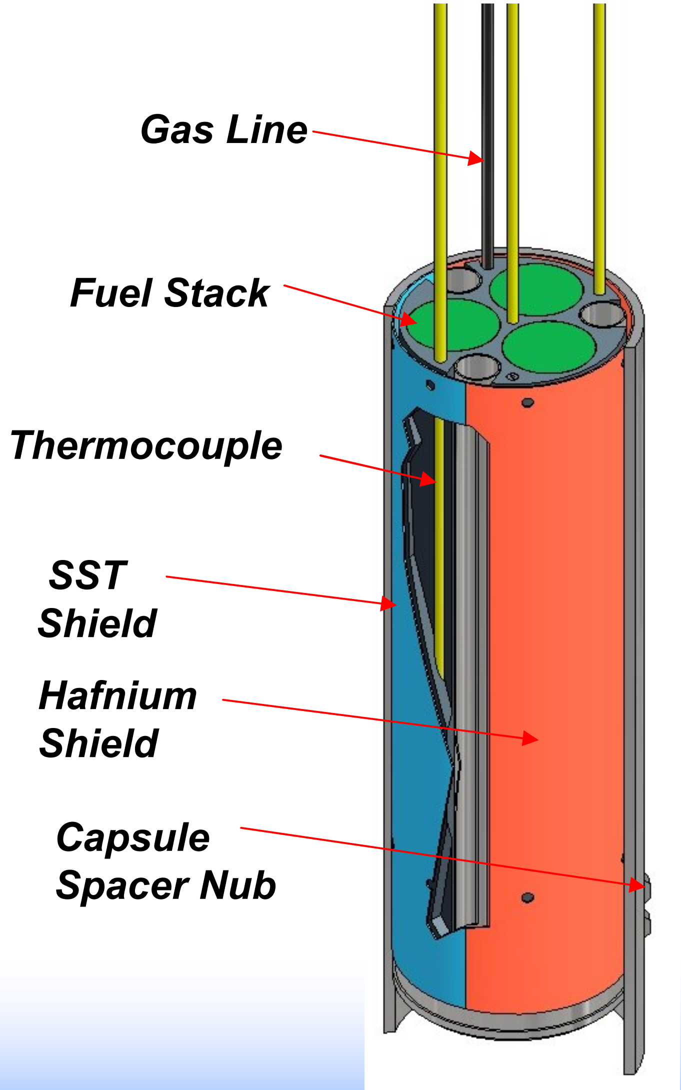
- *Fuel stacks*
  - *3 fuel compacts/level*
  - *4 levels/capsule*
  - *Total of 12 fuel compacts/capsule*
  - *Surrounded by nuclear grade graphite*
- *Thru tubes*
  - *Provide pathway for gas lines & TC's between capsules*
  - *Maintain temperature control gas jacket*



AGR-1 Capsule Cross Section

AGR-1 Capsule Design Features
(continued)

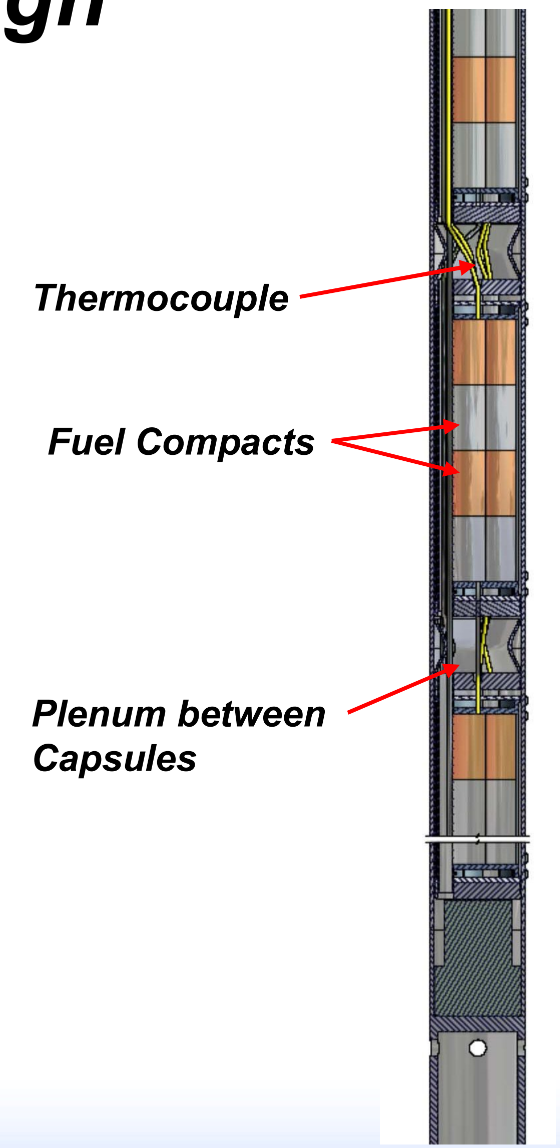
- Fast and thermal flux wires
  - Vanadium/Cobalt for thermal
  - Niobium for epithermal (0.18 MeV threshold)
  - Iron for fast (1 MeV threshold)
- Neutron shrouds
  - Boronated Graphite
  - Hafnium shroud toward core
  - SST shroud away from core to increase flux rate to stack 2



AGR-1 Capsule Vertical Section

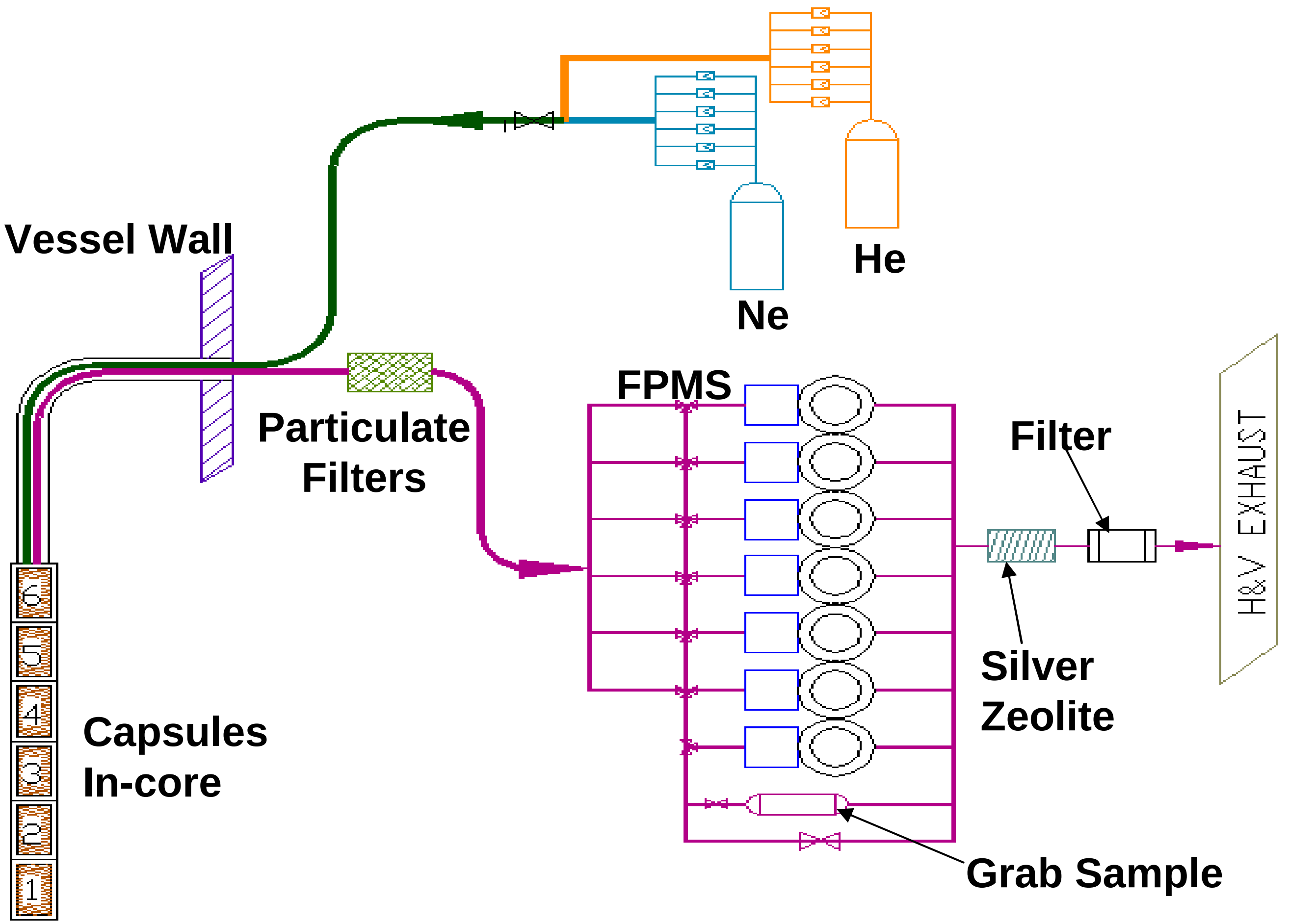
AGR-1 Test Train Design Features

- *6 Capsules in test train*
  - *Capsules are 35 mm in diameter & 150 mm in length*
  - *Individual temperature control and fission product monitoring*
- *Thermocouples*
  - *Mixture of commercial Type N and INL developmental Mo-Nb*
  - *3 TC's in capsules 2 through 5*
  - *2 TC's in capsule 1 (space in thru tubes)*
  - *5 TC's in capsule 6 (no thru tube issues)*
- *Melt wires for temperature back-up for TCs*



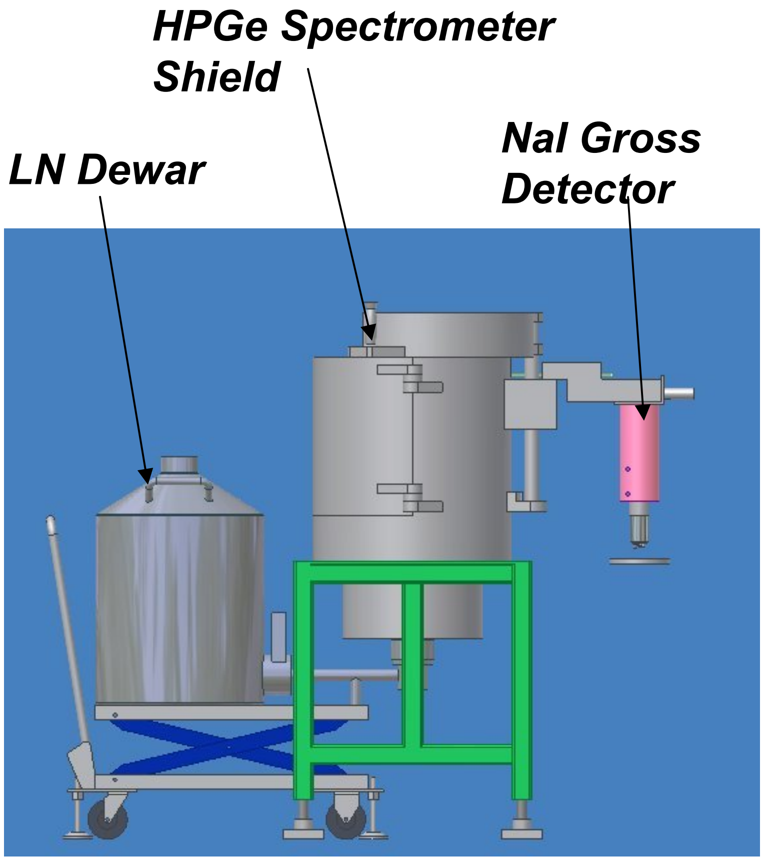
AGR-1 Test Train Vertical Section

AGR-1 Experiment Flow Diagram



AGR-1 Fission Product Monitor

- Individual FPM for each capsule
- Spectrometer
  - Identify & quantify individual fission gases
  - Liquid Nitrogen (LN) cooled HPGe detector
- Gross gamma detector
  - Identify individual particle events up to and including the 250th particle failure
  - Provide release timing
  - NaI crystal scintillation detector
- Seventh FPM to serve as on-line back-up spare
- Grab sample capability



Fission Product Monitor

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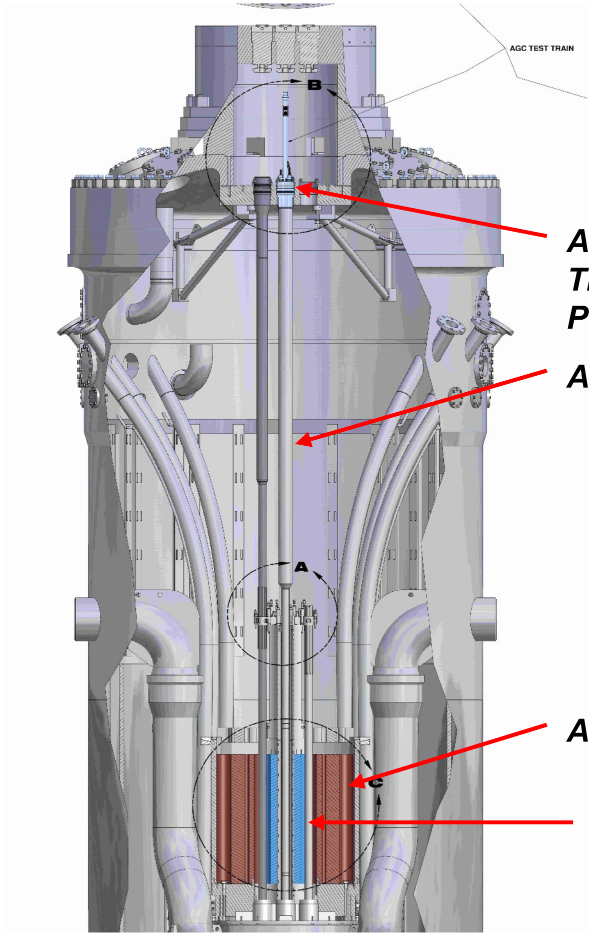
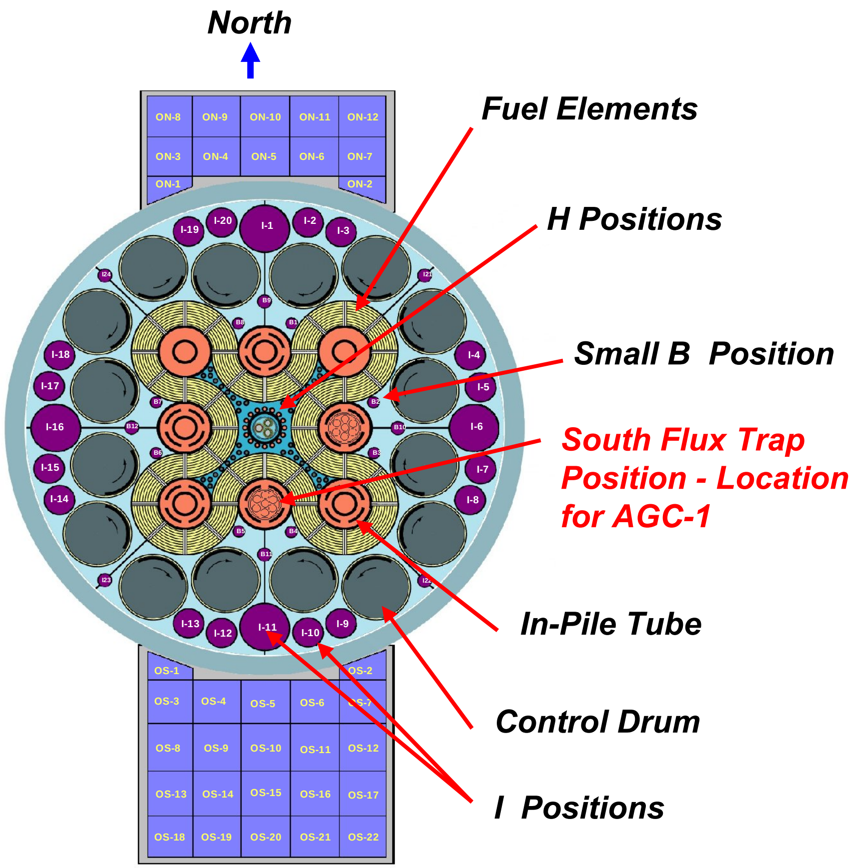
Advanced Graphite Capsule (AGC) Experiment Purpose



AGC-1 Experiment in ATR Reactor Vessel

- ***Nuclear grade graphites used in previous gas reactors are no longer available due to loss of feedstock***
- ***AGC-1 is the first of six graphite irradiations to obtain irradiation creep data***
- ***Experiments will be conducted at:***
  - ***600, 900 and 1200ºC***
  - ***4 to 7 dpa fast neutron damage levels (5.5 and 9.6 x 10^{21} n/cm^2 for E > 0.1 MeV)***
  - ***Compressive loads of 2 to 3 ksi (14 to 21 MPa)***
- ***AGC-1 will be irradiated up to 7 dpa at 600ºC with compressive loads of 2 to 3 ksi (14 to 21 MPa)***

AGC-1 Experiment Location

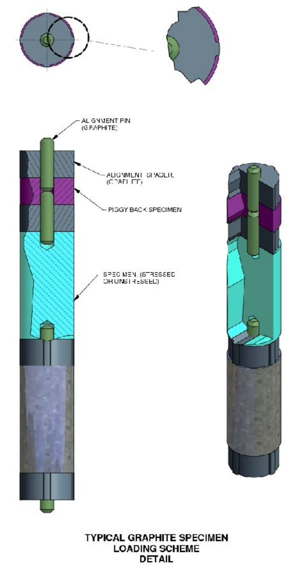


ATR Core Cross Section

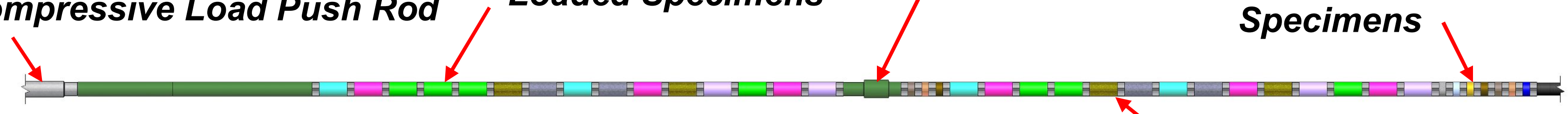
- AGC-1 will be irradiated in the South Flux Trap (SFT) of ATR starting in February 2010.
  - Volume maximizes number of graphite specimens, stacks/channels, loads, and combinations
  - Flux rate minimizes irradiation time to meet NGNP program schedule
  - Experiment will be rotated to minimize flux gradient across experiment diameter

AGC-1 Graphite Specimens

- *Specimen sizes*
  - *Large - Ø ½" (12.5 mm) x 1" (25.4 mm) tall*
  - *Small - Ø ½" (12.5 mm) x ¼" (6.4 mm) tall*
- *6 Perimeter Stacks loaded/unloaded*
  - *15 Large and 2 small specimens per stack compressively loaded above core center*
  - *14 Large and 12 small specimens per stack unloaded below core center*
- *Center Stack (all unloaded)*
  - *172 Small specimens*



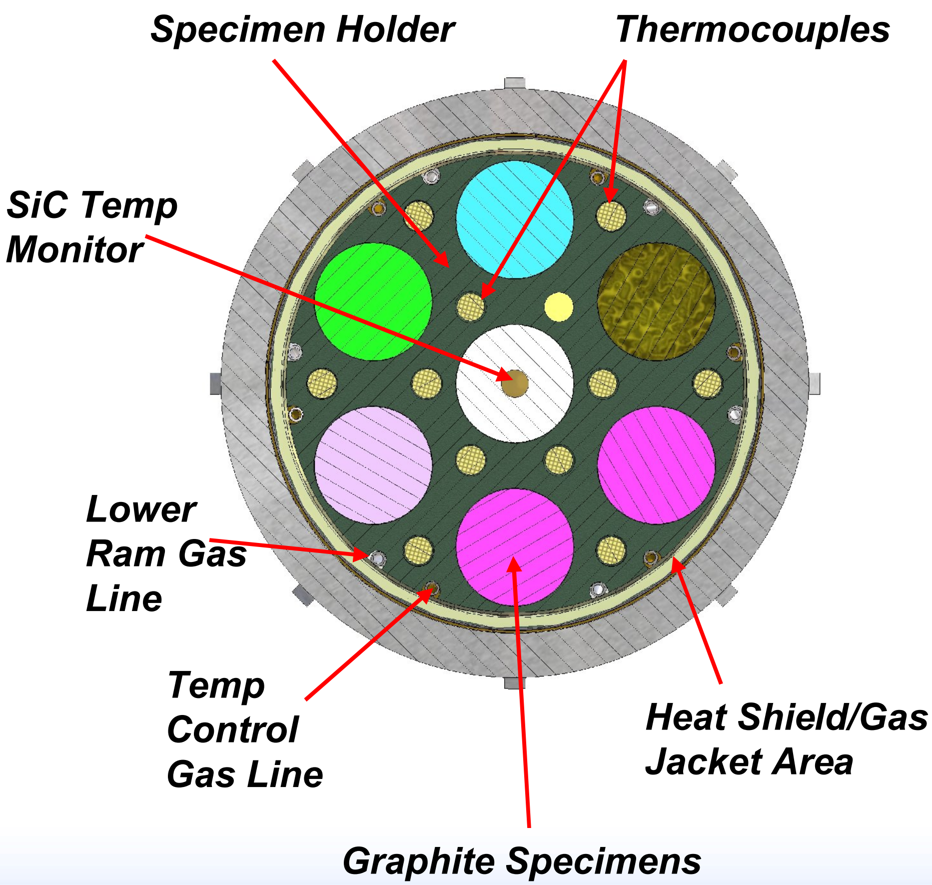
Graphite Specimens



AGC-1 Specimen Stack

AGC-1 Test Train Design Features

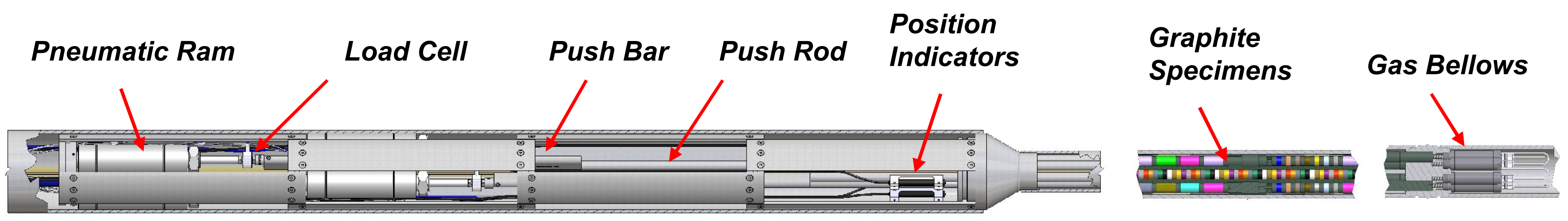
- *6 specimen stacks around capsule perimeter with compressive load on upper half of stack*
- *7th specimen stack in center without compressive load*
- *Graphite specimen holder to contain graphite specimen stacks and TCs*
- *12 TC locations with positions located throughout core height*
- *Flux wires in alignment pins between graphite specimens in peripheral stacks*
- *SiC temperature monitors in center of specimens in center stack*
- *Heat shield between graphite and capsule boundary to limit radiation heat transfer*



AGC-1 Capsule Cross Section

AGC-1 Compressive Load System

- *6 Pneumatic rams above core to provide compressive load on specimens in peripheral stacks during reactor operation*
- *3 Different compressive loads on the peripheral graphite stacks*
  - *2 stacks with 2 ksi (14 MPa) compressive load*
  - *2 stacks with 2.5 ksi (17 MPa) compressive load*
  - *2 stacks with 3 ksi (21 MPa) compressive load*
- *Load cells located between pneumatic rams and push bars to monitor specimen load*



AGC-1 Test Train

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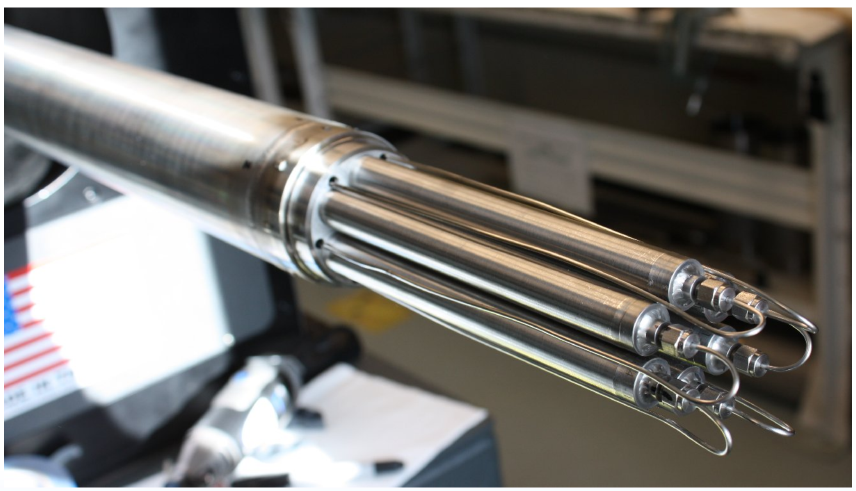
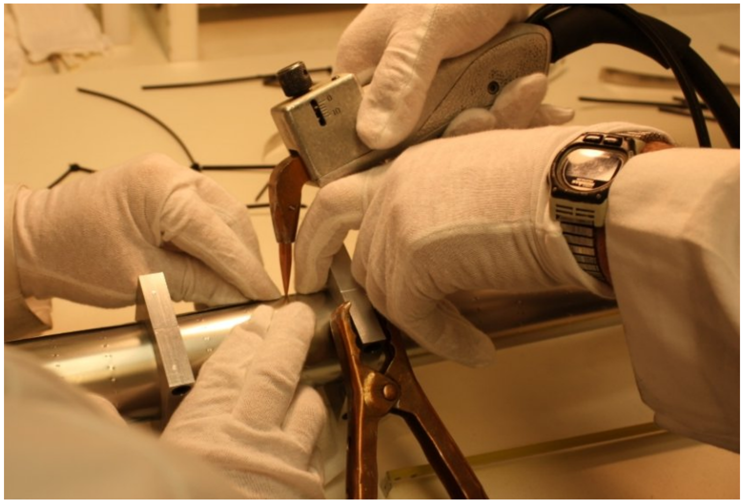
AGC-1 Compressive Load System *(continued)*



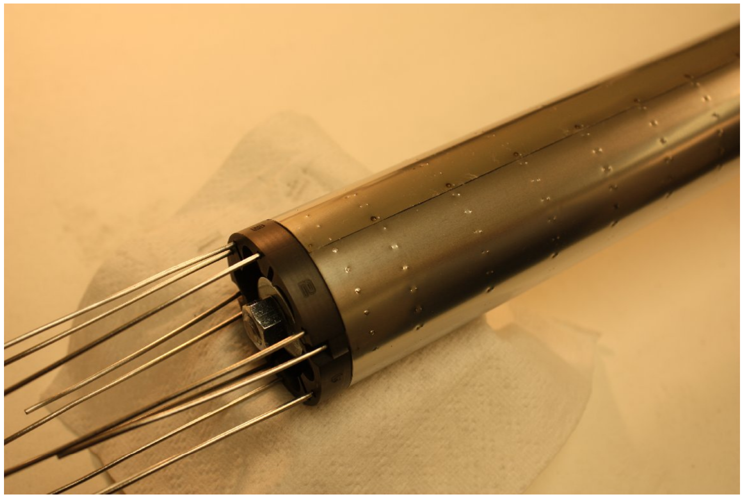
- ***6 Gas bellows below core to vertically lift specimen stacks during reactor outages to verify load conditions***
- ***LVDT Position indicators attached to bottom of push bars to verify specimen movement during outages***
- ***Loads monitored and controlled using same ATR Capsule Distributed Control System (DCS) used to control experiment temperature***

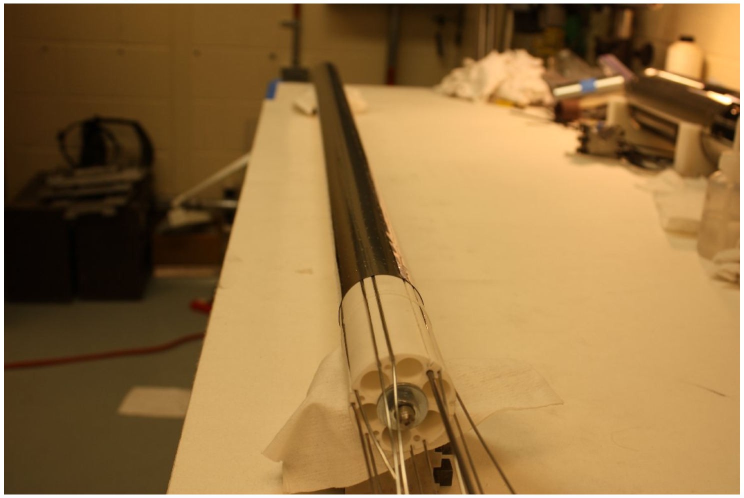
Lower Gas Bellows

AGC-1 Progress & Status



Attaching Heat Shield





AGC-1 specimen holder with thermal shield completed

- *Assembly, Fabrication & Operational Mock-ups tested in 2007*
- *Final design reviews completed in September 2008*
- *Test train assembly & experiment safety analysis approved in April 2009*
- *Experiment scheduled to be inserted and initiate irradiation August 2009 – complete irradiation in late 2010*

MOX Fuel Irradiation

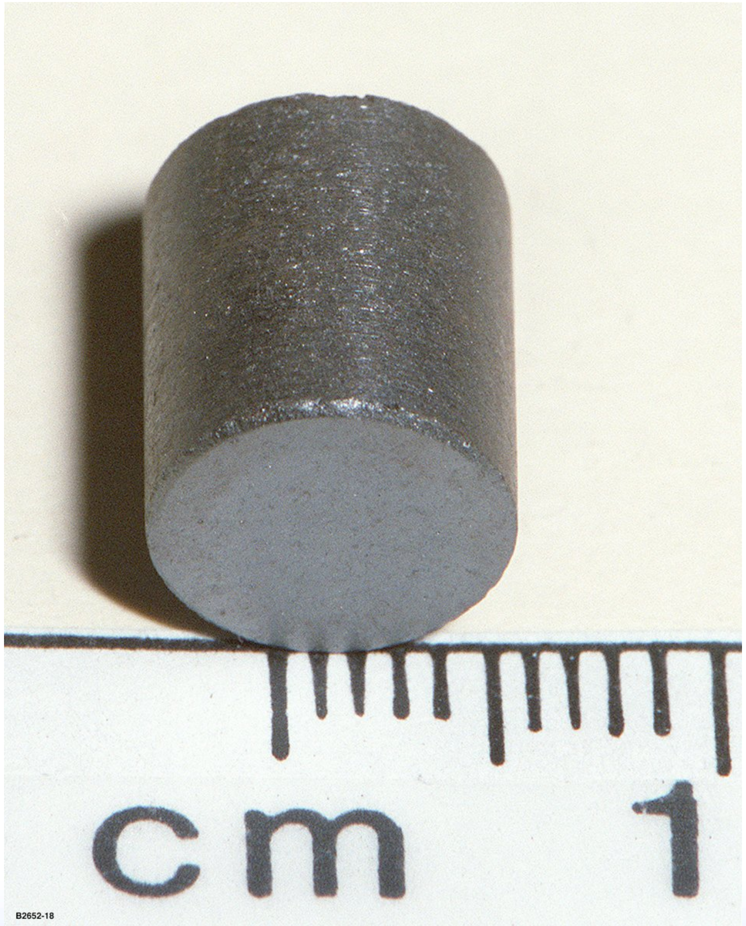
Purpose of the experiment was to obtain Mixed Oxide Fuel (MOX) fuel and cladding irradiation performance data on fuel pins made with weapons grade plutonium.

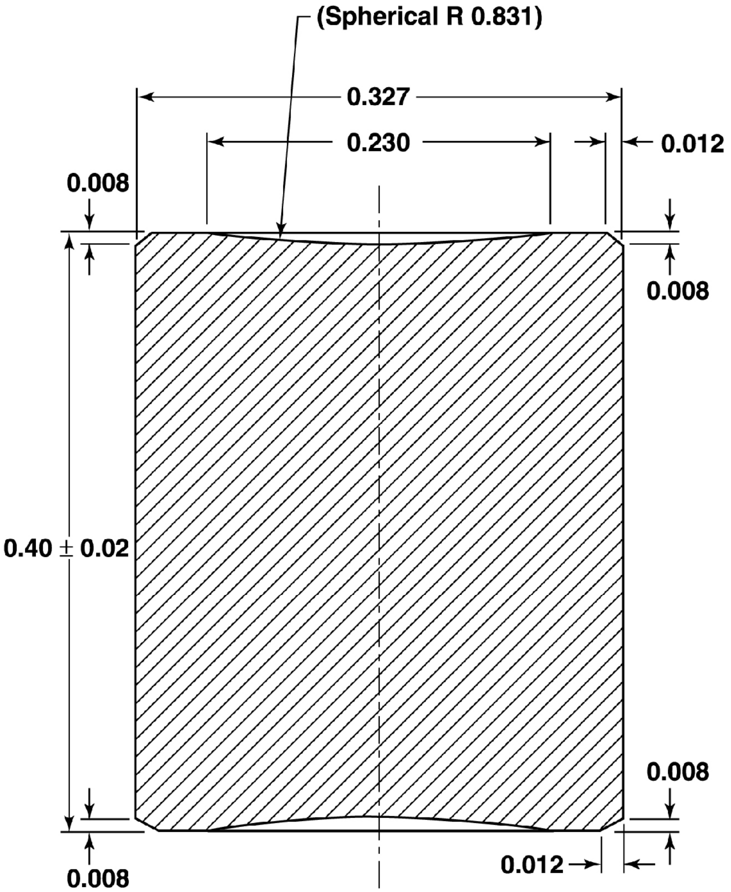
- *Cooperative project between 3 DOE National Laboratories*
  - *Oak Ridge National Laboratory (PM, design, analysis, PIE)*
  - *Los Alamos National Laboratory (fuel fabrication)*
  - *Idaho National Laboratory (design, analysis, irradiation)*

MOX Fuel Irradiation Requirements

- PWR temperature at surface of fuel pin cladding
- Linear heat rate requirements
  - 6 KW/ft minimum
  - 10 KW/ft maximum
- Fuel burn-up levels
  - 8 GWd/t minimum
  - 50 GWd/t maximum
- Maintain orientation of irradiation basket in relation to ATR core center
- Maintain orientation of fuel pins relative to ATR core center

MOX Test Fuel Pellets





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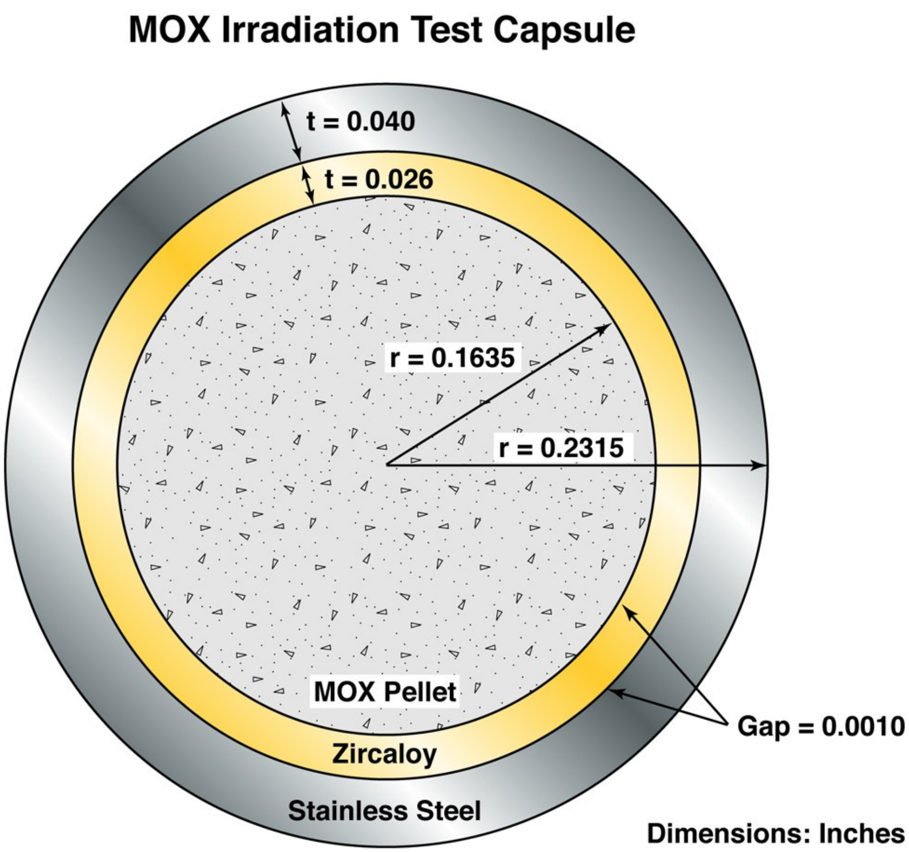
Test Fuel Employed Typical PWR Pellet Dimensions with Normal Dish and Chamfer

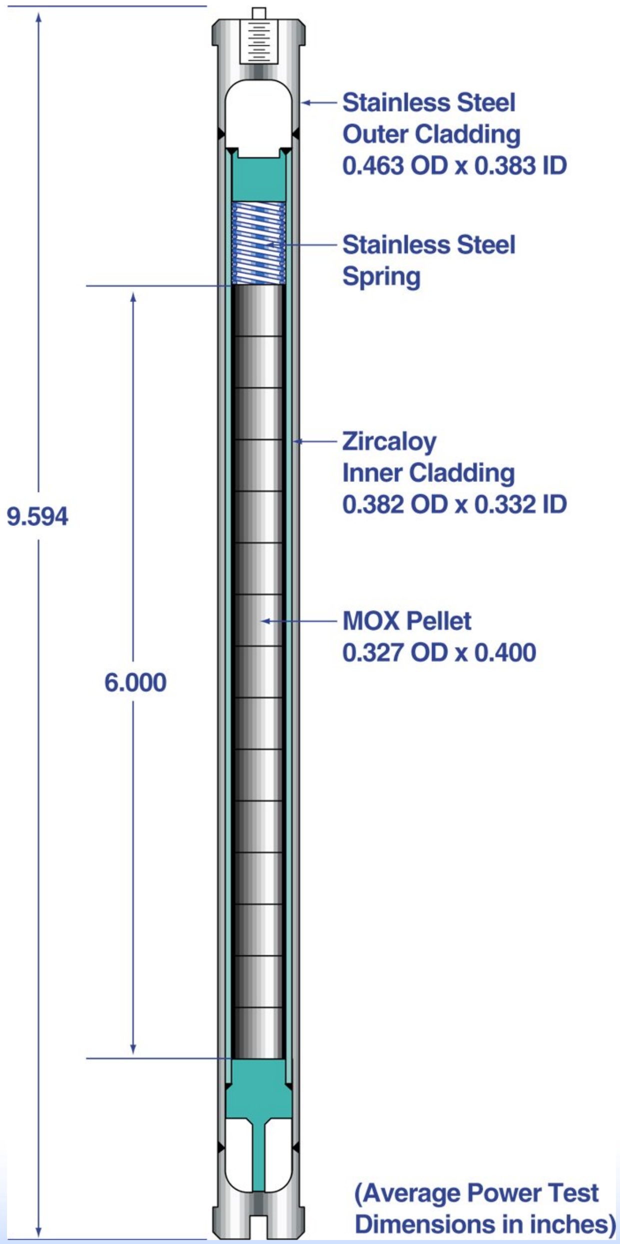
MOX Fuel Capsule Cross Section



- ***Capsule designed to ASME Section III Class 1 requirements***
- ***Small (0.001") insulating gas gap between fuel pin and capsule provided desired temperatures***
- ***Zircaloy fuel pin outer surface protected from***
  - ***Corrosion***
  - ***Hydrogen pickup (hydrides)***

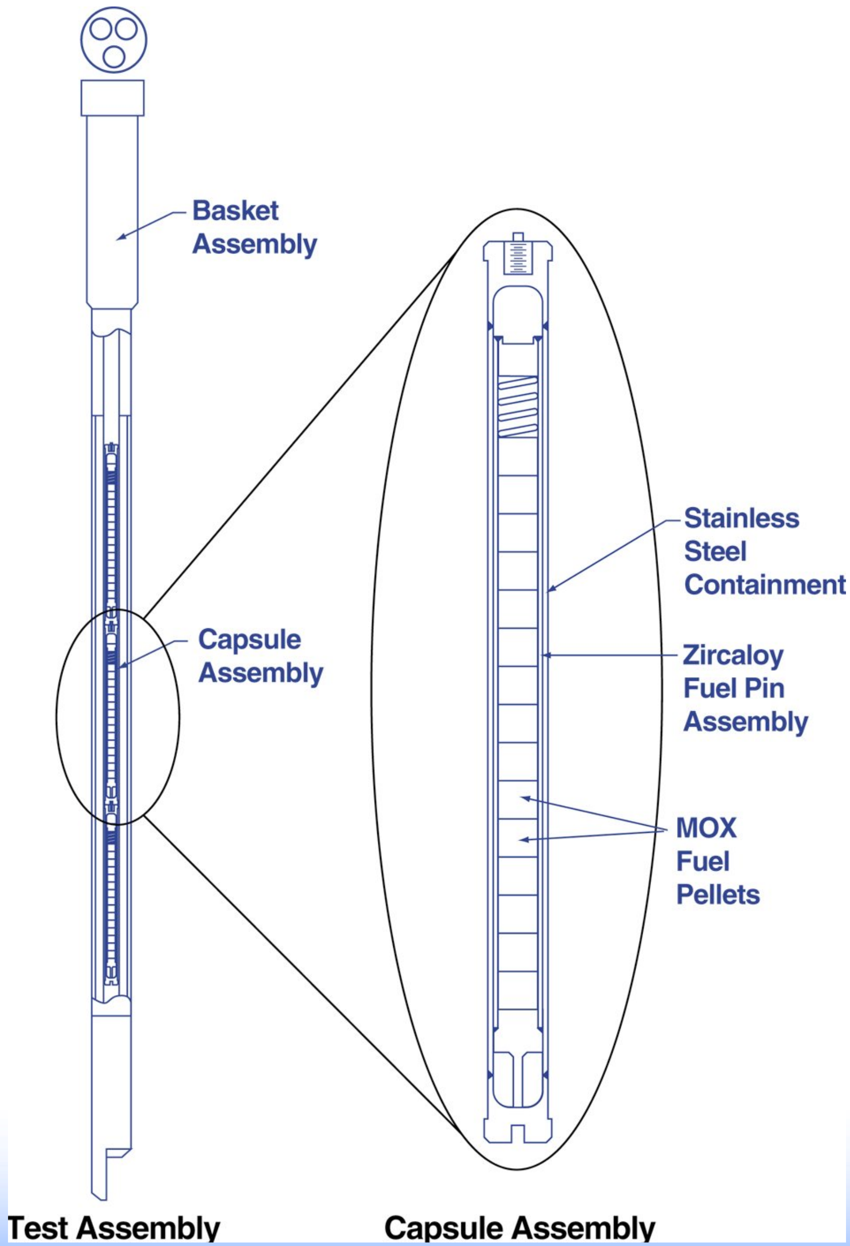
MOX Fuel Capsule Design Features

- *Zircaloy fuel pin*
  - *15 MOX fuel pellets*
  - *Fission gas chamber*
  - *Spring to limit pellet movement*
- *Stainless steel Capsule*
  - *Gas chambers for fuel pin failure & welding caps*
  - *Locating tab on top & bottom heads*
  - *Threaded hole in capsule head for retrieval from basket*



MOX Fuel Basket Design Features

- *Designed for Small (1.5”) I irradiation position*
- *3 Capsules/level with 3 levels in basket = 9 capsules in basket*
- *Centers capsules vertically in ATR Core*
- *Designed with & without neutron shroud*
- *Anti-rotation device on bottom of basket*
- *3 flux wire positions between capsule positions*



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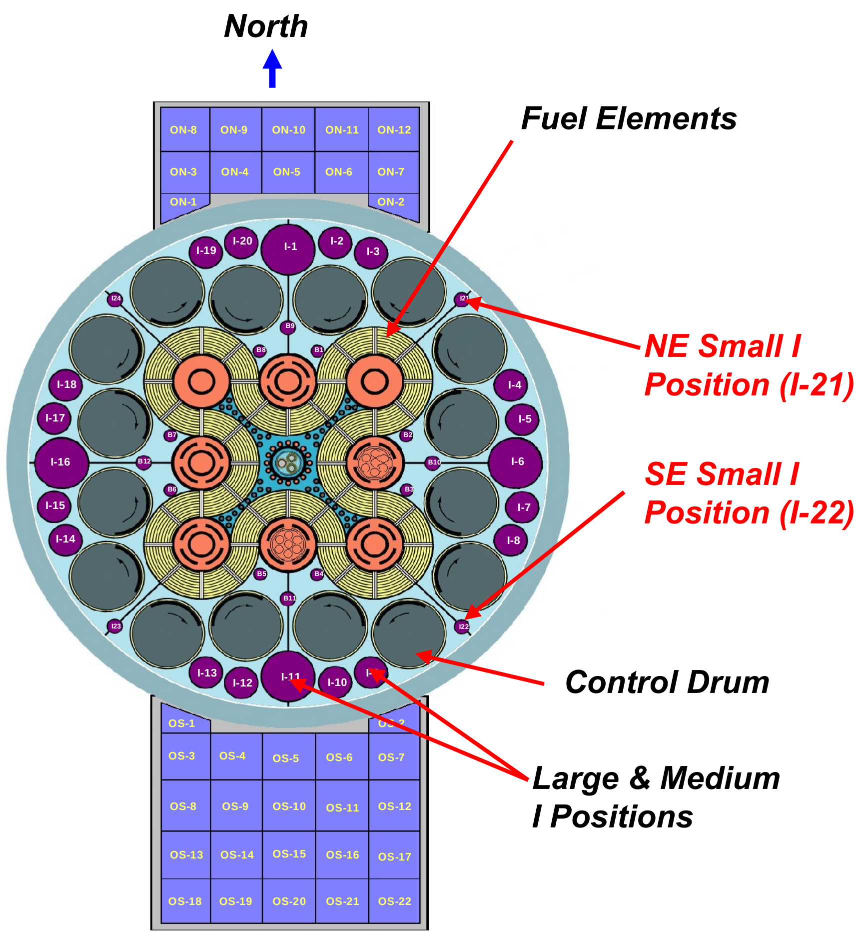
MOX Fuel Experiment Locations



ATR Core Cross Section

- *Irradiation initiated in NE small I position (I-21) in basket with Inconel shroud*
- *As-Run analysis performed to track fuel burn-up*
- *Basket changed to all aluminum basket as fuel depleted*
- *Experiment moved to higher power location in SE small I position (I-22) as fuel continued to deplete*
- *Capsules were "shuffled" vertically & horizontally in basket locations during reactor outages*

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MOX Fuel Capsule Burn-up Levels

Irradiation Phase	Date Completed	Effective Full Power Days	Capsules Withdrawn	Burnup GWd/t
I	Sept. 13, 1998	154.9	1 and 8	8.8
II	Sept. 12, 1999	227.7	2 and 9	21.0
III Part 1	July 23, 2000	232.4	3 and 10	30.2
III Part 2*	Jan. 14, 2001	113.1	—	—
IV Part 1	March 9, 2002	289.1	4 and 13	39.9
• IV Parts 2 and 3	April 18, 2004	443.7	6 and 12	50.1
			5	49.5

*Phase III Part 2 provided catch-up irradiation for capsules 5, 6, and 12 only.

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Thank you for your attention

Questions?